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Laser Induced Fluorescence of Ground State Hydrogen Atoms at Nozzle Exit of an Arcjet Thruster

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Abstract

We report the first observation of a two-photon laser-induced fluorescence (LIF) technique in an arcjet plume. Ground state hydrogen atoms are detected with high spatial resolution near the thruster nozzle exit. Number density, axial and radial velocity, and translational temperature distributions are obtained in the expansion plume of a 1 kW arcjet operating on hydrogen propellant. Comparison of the ground state properties with previously measured excited state hydrogen data and recent computational data is discussed.

Introduction

Arcjets are expected to play an ever increasing role in satellite propulsion needs, primarily stationkeeping and on-orbit maneuvering in the near term. While the technology is considered viable enough to be deployed on a Telstar IV communications satellite for stationkeeping,[1] arcjet technology is far from maturity. In order to compete successfully with chemical propulsion systems for on-orbit missions, further improvements in arcjet propulsion systems are still required.[2] If needed improvements in the performance level and efficiency of arcjets are to be achieved, an increased understanding of the fundamental physical processes that govern the operation of an arcjet is essential. In addition, an ability to predict the plume behavior of a space propulsion device is necessary for prediction and amelioration of spacecraft interactions.

Significant arcjet energy loss results from velocity profile losses due to thick internal boundary layers in the arcjet nozzle and from frozen flow losses such as molecular dissociation. To quantify profile losses, both gas velocity and density distributions must be known. In addition, arcjet models, which are necessary for timely and cost-effective improvements to design, must be tested by comparison with key physical parameters.

At present, only limited inroads have been made into the problem of plume density measurements. For hydrogen arcjet thrusters, determination of species density has previously only been accomplished through the use of Raman spectroscopy[3] on cold flow for molecular hydrogen (more recently for the hot flow case[4]) and absorption spectroscopy[5,6] on arcjet plumes to investigate hydrogen atom densities and some molecular state populations.

For atomic hydrogen measurements, techniques such as VUV and XUV spectroscopy are quite

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exceeding the anode current limit due to the bright arcjet emission background. A gated integrator with a 30 ns gate is used to amplify and average the Hα fluorescence seen by the PMT. Alternatively, the PMT signal can be digitized by a fast oscilloscope to obtain fluorescence lifetimes and quenching information.

The weak UV beam that is sent into the discharge cell is focused with a 150 mm lens. The cell is run with a slow flow of a few Torr of helium carrier gas and a few percent hydrogen. The LIF is detected through a filtered (ungated) PMT. Simultaneous detection of LIF from the cell during each spectral scan of the arcjet LIF provides a zero-velocity comparison from which to measure Doppler shifts.

The procedure for obtaining absolute number density is based on a method reported by Meier et al.[16,17] After a relative number density scan and corresponding lifetime data are taken, the arcjet is turned off and translated away from the collection volume, the chamber is opened, and the calibration discharge cell is placed in the detection volume with the laser beam passing through it. The LIF signal and lifetime is measured for the hydrogen atoms present in the cell due to the microwave discharge. Since the laser beam and detection optics and electronics have remained the same, the LIF from the arcjet and from the cell will have the same proportionality to absolute number density after correcting for any differences in quenching:

$$N_H^A = \frac{S^A}{S^C} \cdot N_H^C \cdot C_Q$$

S^A and S^C are the signal sizes (integrated over the entire spectral width) from the arcjet and the cell, N_H^A and N_H^C are the absolute number densities of atomic hydrogen in the arcjet and the cell, and C_Q is the scaling factor for the difference in quenching. C_Q is given by the ratio of fluorescence decay rate in the arcjet to that in the calibration cell.

The absolute number density of hydrogen atoms in the discharge cell is obtained using a standard chemical titration method. A dilute mixture of NO_2 in helium is added to the flow between the discharge and the detection region. The NO_2 reacts rapidly with hydrogen atoms, so that the LIF signal decreases until it is gone at the point where the partial pressure of added NO_2 is equal to the partial pressure of hydrogen atoms in the initial flow. Details will be discussed further in a subsequent publication.

All data were taken on a 1-kW-class arcjet designed by NASA Lewis Research Center.[18] The cathode gap was set to 0.07". The arcjet operated at 134V, 10A (1.34 kW) on a hydrogen gas flow of 13.1 mg/s (8.74 slpm) at an operating chamber pressure of 7.33 Pa (55 mTorr). The gas flow and power were chosen to closely match the conditions under which the most complete set of previous diagnostic data for a 1 kW hydrogen arcjet were taken, in order to facilitate comparisons between different data sets and between data and models.[3,8,19] Figure 3 shows the V-I curve of our arcjet, compared with the Stanford system for the same hydrogen flow, which indicates that a very close match has been achieved between the two experimental systems. The hydrogen flow controller for the arcjet as well as the flow meters for the discharge cell were calibrated using a wet test meter.

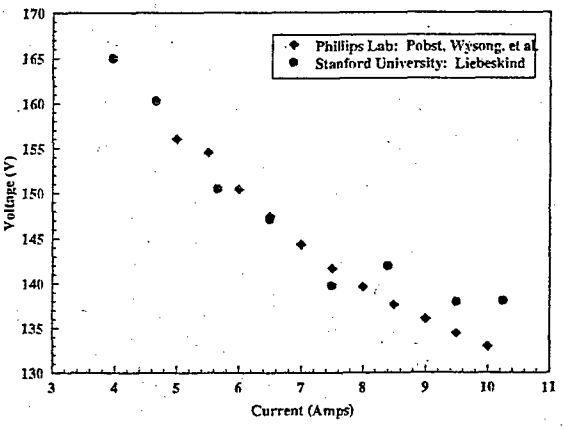

Figure 3. V-I Curve for 1 kW hydrogen arcjet operating with 13.1 mg/s of hydrogen. For comparison, the V-I curve with the same hydrogen flow is shown for the Stanford apparatus. The data is based on specific energy data as described in reference 10.

Results and Discussion

Figure 4 shows a sample spectral scan of the hydrogen atom profile from the arcjet and from the discharge cell, taken with an axial laser beam. Each profile is fit to a Gaussian shape using a Levenberg-Marquardt least squares fit[20] and the wavelength shift of the two centers yields the axial velocity, while the width of each Gaussian yields the

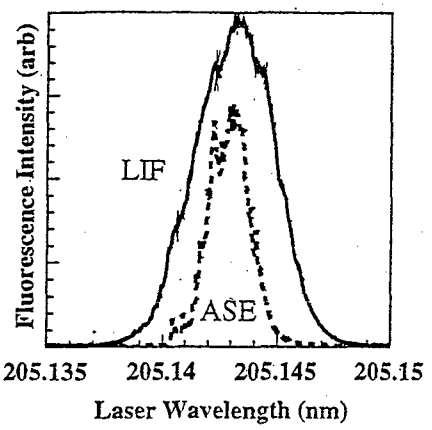

Figure 7. Narrower ASE spectrum compared with LIF spectrum.

Another broadening mechanism that is present is Stark broadening of the transition due to the free electrons present in the arcjet plume. We do not have any direct measurement of the profile of the electron number density for our arcjet, but it has been measured for nearly identical conditions[19] to be less than 2×10^{13} cm^{-3} at the maximum at the center of the nozzle exit plane. This value of n_e would cause a Stark width of 0.002Å[24]. A simulated Voigt profile using this Lorentzian width shows that, for a typical measured linewidth of 0.029Å, accounting for the Stark broadening would cause the temperature from the Doppler portion of the linewidth to go down from 1600K to 1490K. This represents the likely maximum uncertainty in our temperature due to Stark broadening, and will be greatest at the center of the nozzle where n_e is largest.

A small amount of line broadening is caused by the linewidth of the dye laser beam which, unlike that of cw ring dye lasers, is non-negligible compared with the atomic linewidth. The laser linewidth at 205 nm has been measured by taking an LIF spectrum of NO gas in the cell. Since NO is much heavier than hydrogen, and is at room temperature, the width of the rotational lines in the LIF spectrum reflect only the linewidth of the laser (as long as care is taken to use unblended rotational lines). This has shown that the laser has a width of 0.28 cm^{-1} or 0.012 Å at 205 nm. The effect of the laser width is taken into account using the following relation:[25]

$$(\Delta\nu)^2 = (\Delta\nu_D + 2\Delta\nu_l)^2$$

where $\Delta\nu_D$ is the true Doppler width of the line (in cm^{-1}), $\Delta\nu_l$ is the width of the laser, $\Delta\nu$ is the measured transition width, and the factor of two is due to the two-photon probe method.

Figure 8 shows the radial distribution of axial velocities 0.4mm from the arcjet nozzle exit. The velocities were measured with a laser beam entering the plume of the arcjet axially. Figure 9 shows the corresponding distribution of the radial component of velocity when the beam is brought to the plume radially. Data for the plot were taken over several days and the scatter may indicate day to day operational changes in the arcjet as well as measurement uncertainties. It should be noted that velocity profiles of the ground state hydrogen atoms are in close agreement with previous measurements using excited state LIF.[8]

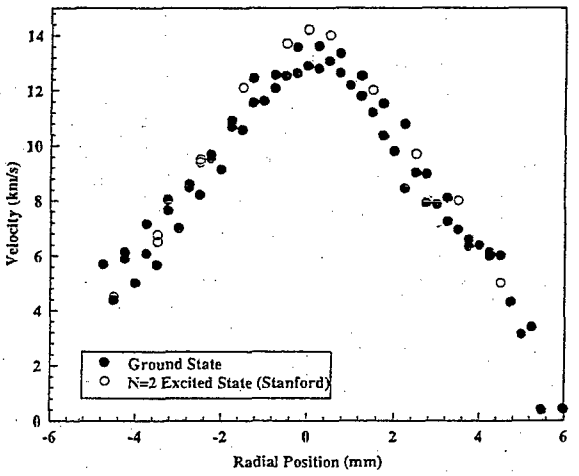

Figure 8. Profile across nozzle exit plane (0.4 mm from exit) of the axial velocity component of the ground state hydrogen atoms containing data from several different days. For comparison, corresponding data (same arcjet conditions, same profile location) for LIF of the electronically excited hydrogen atoms from Stanford University.[8]

Figure 10 shows an attempt to measure any azimuthal or swirl velocity. The laser beam again probes the arcjet radially, but in order to measure azimuthal velocities, the arcjet is translated perpendicularly to the beam (rather than towards or away from it as in the measurement of radial velocity profiles).

We expect the measured velocity component to be zero if the flow is axisymmetric, but it could be non-zero if the gas is swirling. The figure shows that the

equilibrium between the excited state and ground state hydrogen atoms.

The dye laser was tuned to 656 nm in an attempt to directly measure the excited state hydrogen atoms in our arcjet and ensure that the apparent non-equilibrium is real and not due to differences between our system and Stanford's. The Hα LIF was detected, but the power broadening due to the focused, pulsed laser was very severe. Decreasing the laser power enough to alleviate the power broadening led to an unacceptable signal-to-noise ratio, so this measurement could not be pursued.

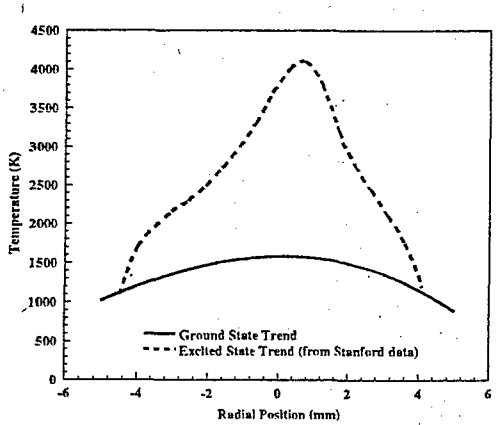

Figure 12. Smoothed temperature profile from data shown in Figure 11, with corresponding data (same arcjet conditions, same profile location) for LIF of the electronically excited hydrogen atoms from Stanford University.[8]

Figure 13 shows two sample fluorescence decay curves, one measured at the center of the nozzle exit plane, and the other measured near the edge of the nozzle exit plane. Change in the lifetime represents the effect of collisional quenching in the 3-2 transition. The curves are obtained by digitizing the LIF signal from the PMT using a 500 MHz oscilloscope. Also shown in the figure is a curve from the laser scatter only (with optical filters removed from the PMT) to show the time resolution of the system with no LIF present. Decay curves such as Figure 13 are analyzed by starting at 10 ns after the laser pulse and fitting the signal to an exponential decay.

Figure 14 shows results for lifetime measurements from two separate runs as a function of position along the nozzle exit. An average of these two values for each position is used to obtain the quenching correction factor as a function of position, which is used to transform the LIF signal profile into a relative number density profile.

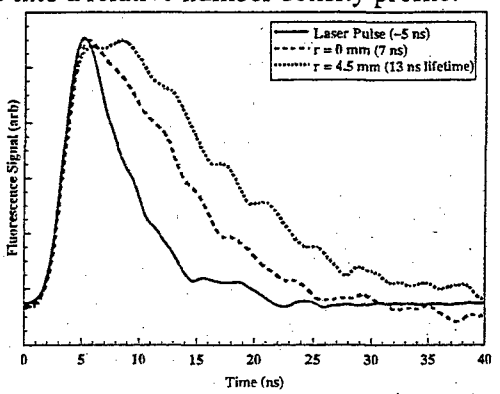

Figure 13. Fluorescence decay for n=3 hydrogen atoms at two positions along the arcjet nozzle exit plane. For comparison, a trace of the laser pulse alone (with no hydrogen atoms present) is shown.

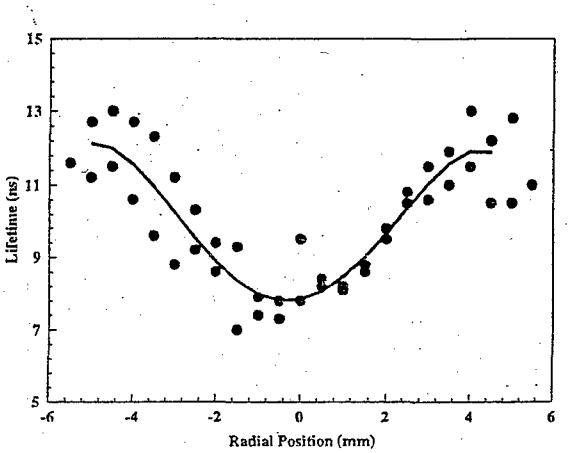

Figure 14. Fluorescence lifetimes as a function of position along nozzle exit from two different days. The line represents a best fit to the data and is used for the quenching correction to convert LIF intensities to relative number densities.

Figure 15 shows the calibrated number density profile of hydrogen atoms at the exit plane of the nozzle. This is obtained from the area under the curve of the hydrogen atom profile (at low laser power to avoid ASE, MPI and saturation), corrected by the fluorescence yield at each location (obtained from the measured fluorescence lifetime profile demonstrating the effects of quenching). The relative number density is then placed on an absolute scale using the calibration procedure discussed above. Separately calibrated data sets from two different days are included in the plot.

Also shown in the figure is the predicted exit plane number density distribution from an arcjet model

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